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Logical-probabilistic model for assessing the reliability of means for preparing and distributing feed

Abstract. In the modern stage of development of animal husbandry, the means used for the preparation and supply of feed mixtures are becoming increasingly common. These facilities combine the operations of loading, grinding, mixing, transporting, and dosed feed distribution. The purpose of this study was to assess and ensure the reliability of the operation of the means for preparing and distributing feed using logic-probabilistic modelling of failures of the feed mixture unloading mechanism as a subsystem of the "Man-Machine-Environment" technical system. In the study, logical-probabilistic modelling of the means for preparing and distributing feed was used as complex technical systems depending on the influence of the components "man-operator", "machine", "environment". The shortest paths of failures and the minimum cross-sections of their prevention for the research objects were analysed. It was proved that to prevent the failure of the "man-operator" component of the system, it is necessary to ensure sufficient qualification of the personnel, foresee the possible occurrence of errors and ensure their timely elimination. It was confirmed that to prevent failures of the feed mixture unloading mechanism, it is necessary to timely control and adjust the condition of parts during operation and when restoring performance. Furthermore, it was established that the probability of failure of the mechanism will be less important under the condition that the probability of elimination of failures in case of insufficient qualification of the operator and in the case of failure of drive parts will be 0.2. It was found that an increase in the probability of failure of the operator under the condition of insufficient qualification, from 0.5 to 0.9, will lead to an increase in the probability of failure as a result of changes in conveyor tension and the impossibility of adjusting conveyor tension, while at 0.9, the probability of failure of the mechanism will be 0.046. The practical significance of the results lies in the possibility of investigating the probability of failure of the feed mixture unloading mechanism based on the reliability of the components of the means for preparing and distributing feed, including drive parts, conveyor belts

Keywords: reliability of machines; a complex technical system; feed mixture unloading mechanism; human operator; environment

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INTRODUCTION

One of the key factors influencing the productivity and health of animals is the feeding process. Countries with a developed agricultural sector of the economy use modern achievements of Industry 4.0 and IT technologies in precision animal husbandry, including global positioning technologies, geographic information systems, technologies for assessing animal productivity and others, which received the greatest development in 2010-2020 (Morrone *et al.*, 2022). T. Norton *et al.* (2019), U. Moallem & L. Lifshitz (2020) note that the efficiency of the livestock industry depends on the features of the technology of preparing and distributing balanced feed mixtures for diverse groups of animals and poultry. Thanks to these implementations, it was possible to use the most innovative systems to improve livestock management approaches. O. Zagurskiy *et al.* (2022) noted that innovative measures can also include a set of ecological principles that are recommended to be implemented in the production activities of livestock enterprises. This will enable scientifically sound decisions in the implementation of social and ecological measures in animal husbandry.

According to K.D. Astanakulov *et al.* (2020) at the current stage of animal husbandry development, both in global practice and in Ukraine, to prepare feed mixtures, machines and equipment for the preparation and distribution of feed, which combine the operations of loading, grinding, mixing, transportation, dosing, and distribution are becoming increasingly common. The world practices of the development of the livestock industry show that in recent decades, the main equipment for preparing and distributing feed is equipment consisting of a frame with a running part, a hopper, a loading mechanism, a grinding-mixing mechanism, and a mechanism for distributing the fodder mixture (Loveikin *et al.*, 2022).

According to T. Fuyang *et al.* (2020), in recent decades in the agrarian sphere, a considerable renewal of machinery and equipment for animal husbandry, including means for preparing and distributing feed, can be observed. Machines and equipment are being updated not only as a result of the commissioning of modern foreign and domestic models of means for preparing and distributing feed, but also as a result of replacing machines with horizontal augers of the grinding-mixing mechanism with corresponding means with vertical augers.

The practices of using and ensuring the performance of means for preparing and distributing feed with vertical screws indicate that foreign samples of these machines have improved technical characteristics, including fairly high operational reliability (Khmelovskyi *et al.*, 2020; Ruzhylo *et al.*, 2022). Therewith, the practice of using machines and equipment in animal husbandry indicates that the intensity of their operation is increasing, most of them have completed their depreciation period, and their operating modes and storage conditions require special attention and constant control of engineering and technical workers, machine operators, maintenance repairmen, service workers.

In recent years, scientific works have emphasized the importance of using technological equipment for the preparation of feed mixtures for cattle on livestock farms specializing in the production of dairy products and beef. A special place in the research of the constructions of feed mixers is occupied by systems of automated control and control of the component composition of feed included in feed mixtures, the data processing method for determining the parameters of work modes was substantiated. The purpose of this study was to ensure the reliability and efficiency of the functioning of means for preparing and distributing feed employing logical and probabilistic modelling of the occurrence of failures of mechanisms as complex technical systems "Human-Machine-Environment".

LITERATURE REVIEW

V. Bulgakov *et al.* (2019) pointed out that the problem of ensuring the efficient and reliable operation of mobile agricultural machinery, including means for preparing and distributing feed, is becoming increasingly urgent, since the speed of its ageing considerably exceeds the pace of their improvement and technical re-equipment of agricultural enterprises of Ukraine. Therefore, to predict the failure of means for preparing and distributing feed, as well as to prevent emergencies on a livestock farm, the issue arises of assessing reliability indicators, determining their residual resource, and establishing the probability of failure-free operation (Banniy *et al.*, 2022). Along with determining the degree of efficiency and reliability of the machine, it is also important to determine the impact of the human operator or other workers on its operation. But according to research results (Najafi *et al.*, 2015; Novitskiy *et al.*, 2016), the efficiency of agricultural machinery operation depends not only on the specific features of the work process, the efficiency of maintenance, and the reliability of the component mechanisms, but on the qualifications and experience of the service personnel.

Analysis by A. Novitskiy *et al.* (2016) shows that as the complexity of agricultural machines increases, the consequences of failures continue to increase, they become more critical. This is especially inherent in the complex "Human-Machine" and "Human-Machine-Environment" technical systems. Therefore, to identify bottlenecks in the "Human-Machine" and "Human-Machine-Environment" systems and establish the influence of the main components or subsystems on the probability of failures, an analysis of their reliability is necessary. It is also important to pick a suitable method of collecting and processing information for quantitative analysis of the reliability of complex technical systems.

In previous studies, Z. Ruzhylo *et al.* (2022) note that the means for preparing and distributing feed structurally, from the standpoint of ensuring reliability, can be presented as a block diagram of sequentially connected subsystems: loading, grinding-mixing, unloading of feed mixture, frame with chassis. The presented subsystems are quite

complex and include a considerable number of elements. The study of literary sources and the conducted research on the problem of ensuring the reliability of means for preparing and distributing feed indicate that the specified issue was understudied in terms of the mechanism of discharge of feed mixture, considering the components of the system "human", "machine", "environment". O. Voinalovych *et al.* (2019) substantiated that the main characteristics of a tool for preparing and distributing feed as a complex technical system, used to investigate reliability according to the method of logic-probabilistic modelling are as follows: failure time, recovery time; failure probability; probability of failure-free operation.

Several methods can be used to determine the reliability indicators of complex "Human-Machine-Environment" technical systems, including:

- simulation modelling and system analysis (Bulgakov *et al.*, 2017; Amaya-Toral, *et al.*, 2022);
- logic-probabilistic modelling, failure tree and block diagrams (Leangsuksun *et al.*, 2003; Ruzhylo & Skorokhod, 2005; Li *et al.*, 2013), method of spatial states (Hrinkiv *et al.,* 2020; Ondar *et al.,* 2020);
- a method of failure analysis based on a survey of experts (Pisarenko *et al.,* 2019; Lo *et al.,* 2019; Aulin *et al.,* 2020).

In modern scientific literature, many studies investigate the construction and analysis of logic-probability models. The study (Novitskiy *et al.*, 2016) presents an analysis of the possibilities of using logic-probabilistic modelling in evaluating the reliability of machines, presents the general principles and features of building models, offers a methodology for development and analysis with their further application on particular systems of feed mixers and feed distributors.

MATERIALS AND METHODS

The results of theoretical and experimental research presented in the study are a continuation of previous studies (Novytskiy & Ruzhylo, 2012; Novitskiy *et al.*, 2016; Ruzhylo *et al.*, 2022) and are aimed at increasing the efficiency of use and ensuring the reliability of livestock machinery and equipment, including means for preparing and distributing feed. To estimate the reliability of the tool for preparing and distributing feed as a complex technical system in operating conditions, statistical data were obtained according to the specified indicators. To solve the purpose and tasks of this study, a logical-probabilistic model was formed for assessing the reliability of the feed mixture unloading mechanism, as a component of the "Human-Machine-Environment" system, using the example of a tool for preparing and distributing feed, the "Profile" shredder-distributor of the "KUNH Ukraine" company (Operator's manual..., 2018). The logic-probability model was researched and formed at the National University of Life and Environmental Sciences (NULES) of Ukraine. During the study, the reliability of 11 shredder-distributors "Profile 12.2-14.2", which were operated in the farms of Khmelnytskyi ("Profile 14.2"), Cherkasy ("Profile 12.2"), and Vinnytsia regions ("Profile 14.2"), was monitored.

The model of formation of failures of the feed mixture unloading mechanism began with the study of the structure, technical characteristics, features of operation, maintenance of serviceability, maintenance of working capacity, establishment of dangerous situations. Dangerous situations were established, which form the sequence of failure and recovery flows. For the logical-probabilistic theory, the analytical description of dangerous situations was performed using logical functions of system failures. The arguments for the failure functions of the means for preparing and distributing feed (system) were initial conditions and initial events. Three components were the starting conditions for the feed mixture unloading mechanism: operator error, failure of mechanism parts; position of the mechanism; unsatisfactory condition of the environment or feed components. Initial conditions were considered for each component. For the first component of the complex technical "human-operator" system, the initial conditions were as follows: insufficient qualification; the occurrence of an error; untimely elimination of the error. Failures of the "machine" component were caused by failure of parts of the unloading conveyor; violation of the position of the conveyor belt; change of conveyor tension; the absence of the ability to adjust the tension of the conveyor. The initial events of the unsatisfactory state of the environment (feed components) were as follows: adverse impact of the environment; unsatisfactory properties of feed components and their contamination; the state of the floor surface in the premises of the livestock farm where the feed mixture is unloaded.

After compiling and testing the sequence of dangerous situations, system failure functions were compiled – the shortest paths of failure of the feed mixture unloading mechanism. Previous studies of means for preparing and distributing feed (Novytskiy & Ruzhylo, 2012) established that the reliability of the feed mixture unloading mechanism is limited by the following elements: hydraulic cylinder; drive details; conveyor belt. From the experience of using the means, it was known that the bearings of the conveyor axle and the hydraulic cylinder of the conveyor were characterized by gradual wear and failure, and emergency ones lost serviceability or performance as a result of failures of shaft bearings and drive chains.

The tool for preparing and distributing feed was controlled and serviced by a human operator, who was a component of the complex technical system "Human-Machine-Environment". Two important conditions were considered during the formation of the logical-probabilistic model of the occurrence of failures of the feed mixture unloading mechanism:

- all initial conditions and initial events that could affect the probability of failure were considered;
- all proposed initial conditions and initial events were accepted by specialists in this field.

When using the mathematical apparatus of logical-probabilistic modelling, the specified conditions were considered and implemented. For the mathematical description of the presented logical-probabilistic model, logical functions of system failures were used, which are presented in the form of an event matrix.

RESULTS AND DISCUSSION

The formation of a logic-simulation model of failures of the mechanism (subsystem) for discharging the feed mixture of the means for preparing and distributing feed includes:

- establishing a sequence of dangerous situations – subsystem failures;
- analytical description of the dangerous state of the mechanism using logic functions of system failures;
- setting arguments of subsystem failure functions, which are initial conditions and initial events;
- approbation of the sequence of dangerous situations and compilation of subsystem failure functions – the shortest failure paths.

The sequence of formation of failure of the feed mixture unloading mechanism can be presented in the form of a logic-probabilistic model (Fig. 1).

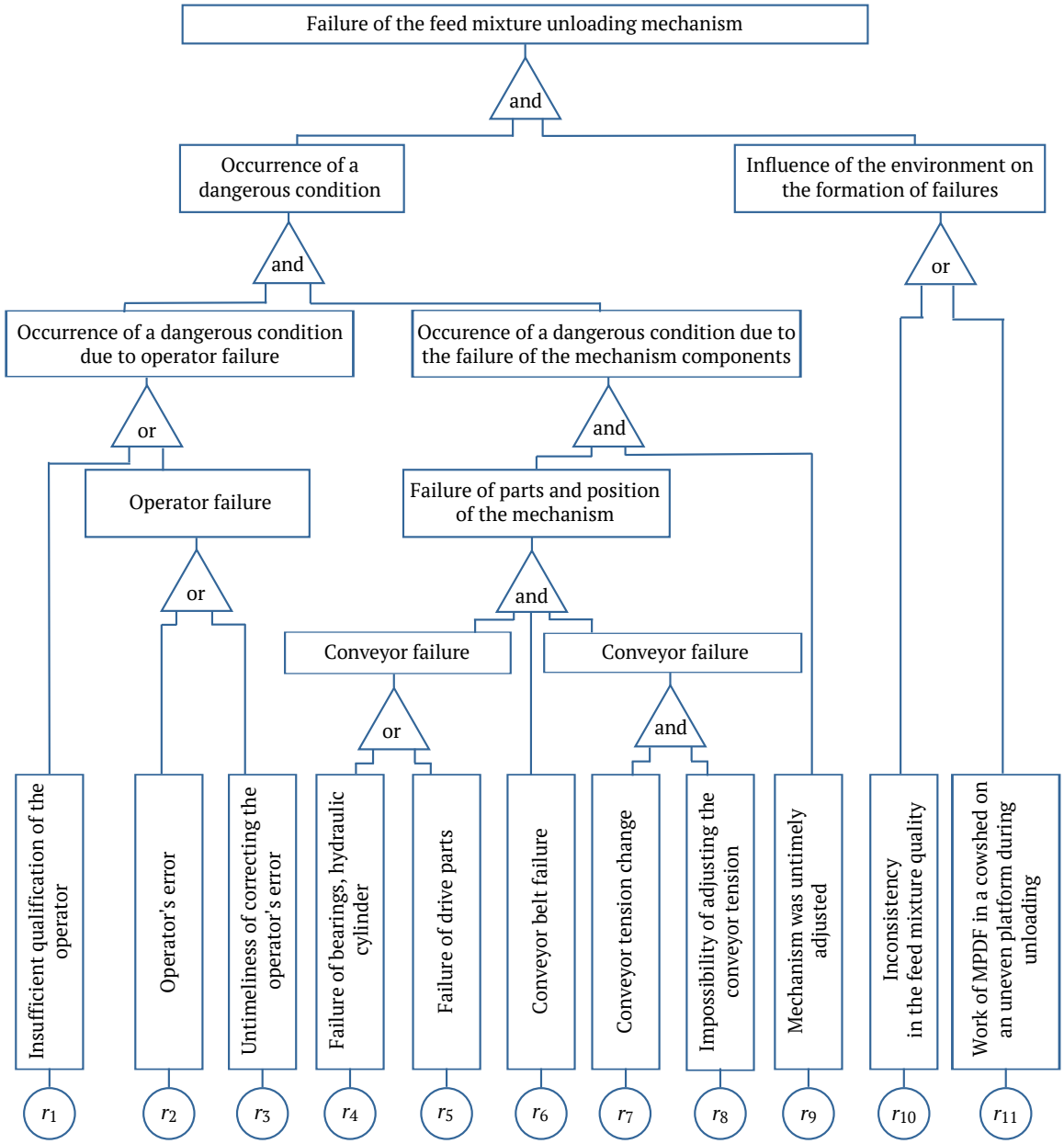

Figure 1. A model of formation of failure of the feed mixture unloading mechanism
Source: developed by the authors based on (Novytskiy & Ruzhylo, 2012)

Failures of mechanism parts, the inability to timely adjust individual components, personnel errors and an unsatisfactory state of the environment, i.e., events describing the causes of the dangerous situation of the

subsystem, have only two states – "there is an event" (failure of an element, operator error, state of the environment) or "no event", but they form a complete group of events. The set of causes of failure functions of the subsystem was denoted by r_i, where i is the serial number of the logical variable. Based on the obtained logic-probability model, the subsystem of the means for preparing and distributing fodder will fail, i.e., the event "failure of the feed mixture unloading mechanism" will occur, if the following initial conditions are fulfilled: failure of the operator (r_1–r_3); failure of mechanism components, including mechanism details and positions (r_4–r_9); the influence of the environment or the condition of the feed mixture on the formation of failure (r_{10} and r_{11}). One of the limitations that is considered when creating a logical-probabilistic model is the consideration of all initial events and conditions that lead to the failure of the mechanism as a whole. For the mathematical description of the presented model, it is appropriate to use the logical functions of mechanism failures, which were written in the form of a logical matrix of initial conditions r_i (Novytskiy & Ruzhylo, 2012):

$$y_c(r_1,\dots,r_{11}) = \begin{vmatrix} r_1 \\ r_2 \\ r_3 \end{vmatrix} = \begin{vmatrix} r_4 \\ r_5 \\ r_7 r_8 \end{vmatrix} = |r_9| = \begin{vmatrix} r_{10} \\ r_{11} \end{vmatrix}. \quad (1)$$

The function (1), obtained from the results of the simulation of the failure of the feed mixture unloading mechanism (Fig. 1), is monotonous and repetitive, since the replacement of any element that failed with a serviceable one, or the reservation of an event that affects the formation of the failure, will not lead to subsystem failure (Bunda *et al.*, 2020). When opening the parentheses, the logical functions of subsystem failures were obtained in the form of a disjunction of the 24 shortest failure paths (2).

$$y_c(r_1,\dots,r_{11}) = \begin{vmatrix} r_1 r_7 r_8\, r_9\, r_{10} \\ r_1 r_7 r_8\, r_9\, r_{10} \\ r_1 r_6 r_9 r_{10} \\ r_1 r_6 r_9 r_{11} \\ r_1 r_4 r_9 r_{10} \\ r_1 r_4 r_9 r_{11} \\ r_1 r_4 r_9 r_{10} \\ r_1 r_4 r_9 r_{11} \\ r_2 r_4 r_9 r_{10} \\ r_2 r_4 r_9 r_{11} \\ r_2 r_5 r_9 r_{10} \\ r_2 r_5 r_9 r_{11} \\ r_2 r_6 r_9 r_{10} \\ r_2 r_6 r_9 r_{11} \\ r_2 r_7 r_8\, r_9\, r_{10} \\ r_2 r_7 r_8\, r_9\, r_{11} \\ r_3 r_4 r_9 r_{10} \\ r_3 r_4 r_9 r_{11} \\ r_3 r_5 r_9 r_{10} \\ r_3 r_5 r_9 r_{11} \\ r_3 r_6 r_9 r_{10} \\ r_3 r_6 r_9 r_{11} \\ r_3 r_7 r_8\, r_9\, r_{10} \\ r_3 r_7 r_8\, r_9\, r_{11} \end{vmatrix}. \quad (2)$$

The study and detailed analysis of the failure formation model of the feed mixture loading mechanism (Fig. 1) and matrix (2) helps assert that the risk of failure is associated with one of 12 different failure formation methods. By transforming formula (2), one can obtain the logical functions of system failures in the form of a disjunction of 5 minimum sections of failure prevention:

$$y_c(r_1,\dots,r_{11}) = \begin{vmatrix} & r'_9 & \\ r'_1 & r'_2 & r'_3 \\ r'_4 & r'_5 & r'_6 \; r'_7 \\ r'_4 & r'_5 & r'_6 \; r'_8 \\ & r'_{10} & r'_{11} \end{vmatrix}. \quad (3)$$

Analysing the obtained matrices (2) – the shortest failure paths and (3) – minimum failure prevention sections, it can be concluded that to prevent failures of the feed mixture unloading mechanism, it is necessary to timely control and adjust the condition of the parts of the mechanism itself (i.e., r_9 and r'_9. The generation of sequences presented in matrices (2) and (3) helps analyse and synthesize the causes of mechanism failures, and accordingly, the need to formulate tasks to strengthen the requirements for the components of the means for preparing and distributing feed as a complex technical system:

$$P_{MUFM} = P\left\{\begin{vmatrix} r_1 \\ r_2 \\ r_3 \end{vmatrix} = \begin{vmatrix} r_4 \\ r_5 \\ r_6 \\ r_7 r_8 \end{vmatrix} = |r_9 = \begin{vmatrix} r_{10} \\ r_{11} \end{vmatrix} = 1\right\} =$$
$$= P_7 \cdot [1 - G_1 \cdot G_2 \cdot G_3)] \cdot$$
$$\cdot\ [1 - G_4 \cdot G_5 \cdot G_6)] \cdot 1 - G_8 \cdot G_9], \quad (4)$$

where G_i is the probability of failure-free operation, P_i is the failure probability.

The analysis of the shortest failure paths and the minimum cross-sections of their prevention indicate that timely control and adjustment of the mechanism (i.e. r_9 and r'_9. Based on the analysis of the logic functions of subsystem failures, which are presented in matrices (2) and (3), it is possible to prevent the loss of efficiency of the feed mixture unloading mechanism and thus reduce the risk of failure of the means for preparing and distributing feed.

It was investigated the influence of the components "Man", "Machine", "Environment" of a complex technical system on the means for preparing and distributing feed and emphasize the impact of components P_1 (insufficient qualification of the operator), P_5 (failure of mechanism drive parts) and P_9 (mechanism untimely adjusted). For the formation model of the failure of the feed mixture discharge mechanism, the influence of components P_1, P_5, and P_9 was studied for the following two cases:

a – probability of eliminating mechanism failures in the case of insufficient qualification of the operator and in the case of failure of drive parts, which are 0.1 in value; the mechanism is untimely adjusted with a probability of 0.5;

b – probability of eliminating mechanism failures in case of insufficient qualification of the operator and in the

case of failure of the drive parts, which are 0.2 in terms of values; the mechanism is untimely adjusted with a probability of 0.99.

The results of the study of the reliability of the feed mixture unloading mechanism are presented, respectively, in Figure 2a and Figure 2b.

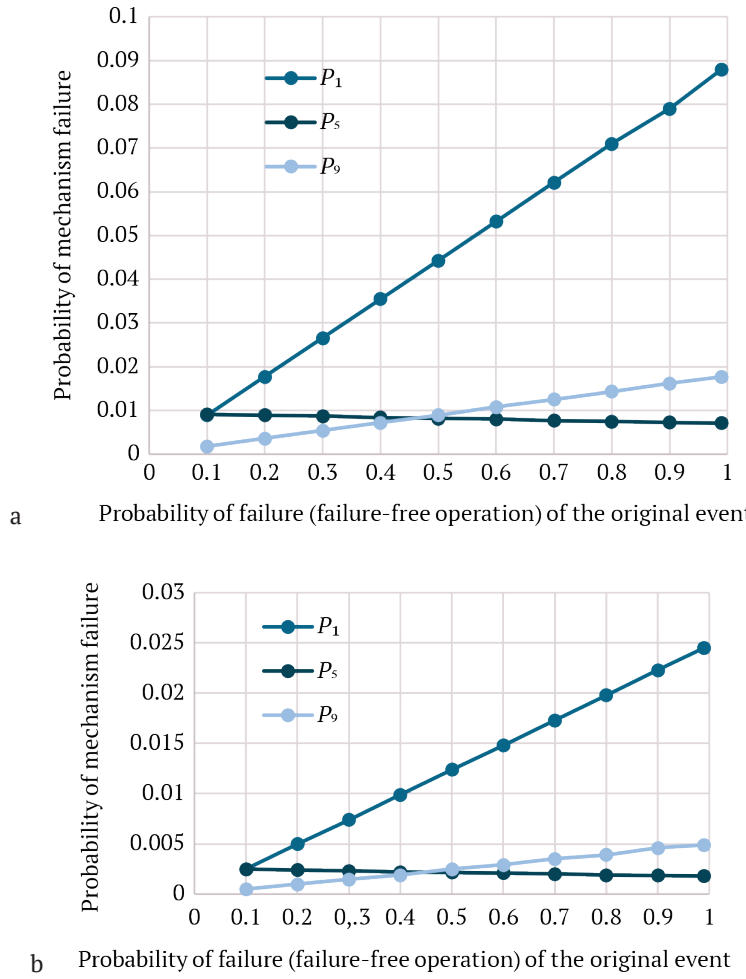

Figure 2. Dependence graph of the probability of failure of the feed mixture unloading mechanism of the means for preparing and distributing feed on the state of components P_1, P_5, and P_9

Source: developed by the authors

The analysis of graphical dependencies presented in Figures 2a and 2b showed that the "human-operator" component has a predominant influence on the possibility of failure of the feed mixture unloading mechanism compared to the influence of the "machine" and "environment" components. The probability of failure of the mechanism is less important under the condition that the probability of eliminating the failure of the mechanism in case of insufficient qualification of the operator and in the case of failure of drive parts is 0.2. Therewith, the probability that the mechanism is untimely adjusted is 0.99.

The analysis of the obtained graphical dependencies (Fig. 2a) suggests that an increase in the probability of failure of the operator's work in case of insufficient qualification, which is 0.1, leads to a decrease in the probability of failure of drive parts, and the probability of failure due to untimely adjustment within 0.5 to 0.99 will increase by 50%, and will be 0.009. The analysis of the obtained graphical dependencies (Fig. 2b) suggests that an increase in the probability of failure of the operator's work in case of insufficient qualification, which is 0.2, leads to a decrease in the probability of failure of drive parts, and the probability of failure as a result of untimely adjustment within 0.5 to 0.99 will increase by 50% but will be 0.005.

For the formation model of the failure of the feed mixture unloading mechanism, we will investigate the influence of components P_1 (insufficient qualification of the operator), $P_{7\text{-}8}$ (change in conveyor tension and impossibility of adjusting conveyor tension) and P_9 (mechanism untimely adjusted) for two cases: the probability of P_1 (insufficient qualification of the operator) is 0.5 (Fig. 3a) and 0.99 (Fig. 3b), respectively.

Figure 3 shows graphical dependencies of the probability of failure of the feed mixture unloading mechanism in case of insufficient qualification of the operator, failure due to a change in the conveyor tension and the

impossibility of adjusting the conveyor tension, untimely adjustment of the mechanism. The logical variable corresponding to the insufficient qualification of the operator is denoted by r_1 (Chovnyuk *et al.*, 2022).

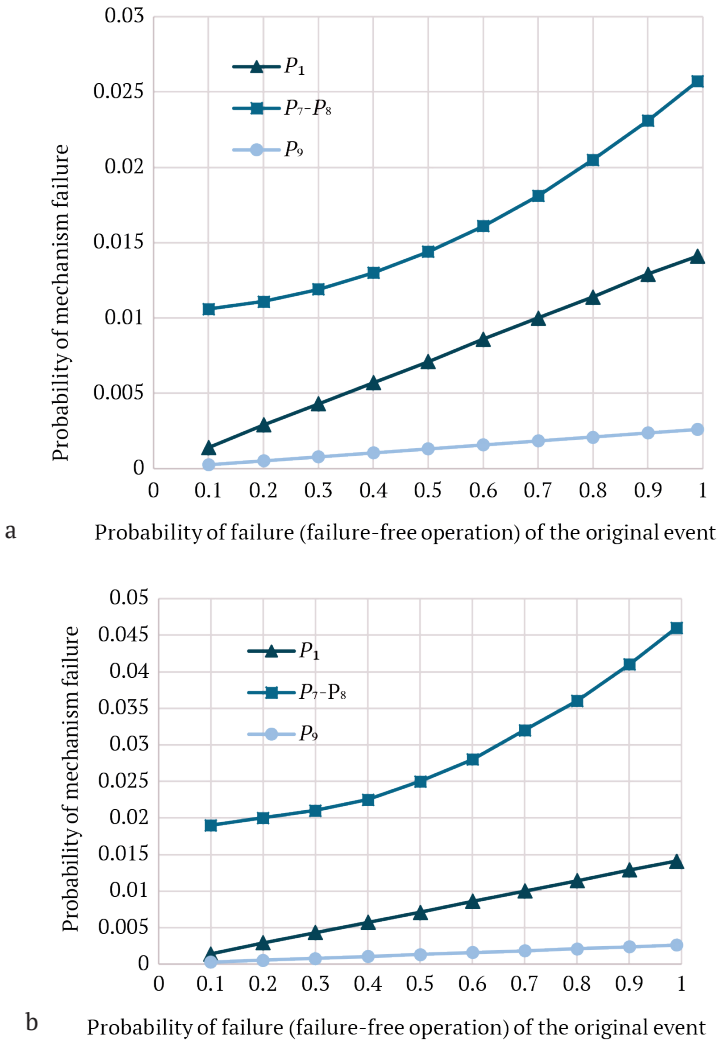

Figure 3. Dependence graph of the probability of failure of the feed mixture unloading mechanism of the means for preparing and distributing feed on the state of components P_1, $P_{7\text{-}8}$, and P_9

Source: developed by the authors

Figures 3a and 3b present a study of the influence of the logical variable r1 of the operator under the condition that the probabilities of occurrence of events are 0.5 and 0.9, respectively. Therewith, the probability of failure of the feed mixture unloading mechanism can take different values if the above-mentioned events are undetected or detected. The analysis of the obtained graphical dependencies (Figs. 3a and 3b) suggests that an increase in the probability of failure of the operator's work under the condition of insufficient qualification from 0.5 to 0.9 leads to an increase in the probability of failure due to a change in conveyor tension and the impossibility of tension adjustment transporter. Therewith, the probability of failure of $P_{7\text{-}8}$ within 0.5 to 0.99 will increase intensively and will reach its maximum value with insufficient qualification: for a value of 0.5, the probability of failure will be 0.026; for 0.9, the probability of failure will be 0.046. The analysis of the shortest paths of occurrence of failures and the minimum cross-sections of their prevention indicate that to prevent failures of the feed mixture unloading mechanism, timely control and adjustment of the mechanism is necessary. Based on the analysis of the logical functions of failures of the feed mixture unloading subsystem, it is possible to prevent the loss of efficiency of the mechanism and reduce the risk of failure of the research object as a whole.

The analysis of theoretical and experimental studies of machines for preparation and distribution of feed suggests that most authors conducted research to establish the operational, structural, and functional parameters of mechanisms for loading feed components and grinding-mixing. To improve the dynamic characteristics and reduce the wear of the unit's elements, V. Khmelovskyi *et al.* (2020),

V. Loveikin *et al.* (2022) propose reducing the amount of rotor imbalance by installing an auger in the form of a two-way conical screw. However, their studies did not assess the influence on the dynamic characteristics of the quantity and scheme of installing knives on the turns of the screw. It is unclear how these recommendations will affect the operation of the feed mixture unloading mechanism.

Design and technological parameters of self-propelled mixers are presented in the study by T. Fuyang *et al.* (2020), where the authors recommend improving the parameters of the loading milling mechanism and the vertical auger of the grinding-mixing mechanism. The article states that to ensure the uniformity and quality of the feed mixture, the rotation speed of the auger should be within 22...26 min^{-1}, and the mixing time of the feed components should be 6...8 min. It would be useful to know how improvements in the loading and grinding-mixing mechanisms will influence the operation of the unloading mechanism and the machine as a whole. Issues of ensuring the reliability of self-propelled mixer mechanisms are still relevant.

V. Bulgakov *et al.* (2017) presented theoretical studies of the parameters of screw working bodies, considered the movement of a particle of material by the working body of an agricultural machine in the form of a vertical screw limited by a coaxial fixed cylinder. S.F. Pylypaka & M. Klendii (2022) obtained the dependences of the change in the speed of transporting a material particle under the influence of the coefficient of friction of the particle on the surface of the screw and the coefficient of friction of the particle on the surface of the limiting vertical cylinder, which can be used when substantiating the parameters of feed mixers and feed distributors. V.M. Baranovsky *et al.* (2018) analysed the technological operations associated with the transportation of agricultural materials in closed, immovable enclosures, which are carried out by screw conveyors and help obtain high efficiency of loading and unloading operations.

The characteristic features of the use of screw conveyors for transporting or lifting bulk materials to different distances and heights are considered by V.G. Gorobets *et al.* (2018), B.M. Hevko *et al.* (2018). In these studies, the impact on the performance of the screw conveyor of such parameters as the volume level of filling of loose material and the speed of rotation of the screw was also investigated. The authors of the presented articles analysed the operating conditions of conveyors, provided the results of theoretical and experimental research into the processes of transportation of agricultural materials, which include grain materials, compound feed, bran, and chaff. The obtained research results can be used to improve and ensure the reliability of operation of shredders-distributors.

Of scientific and practical interest are the results of O. Trokhaniak (2022), which highlight the results of substantiated rational constructive, kinematic, and technological parameters of screw conveyors. The technological processes of the movement of agricultural materials in horizontal, inclined directions, and along curves were investigated.

The analysis strongly suggests that the results of the presented research are not yet sufficiently used in the construction of modern tools for preparing and distributing feed (Baranovsky *et al.*, 2018; Pylypaka *et al.*, 2022; Trokhaniak, 2022).

Ensuring reliability in the implementation of the maintenance and repair system is facilitated by equipping modern foreign and Ukrainian means for preparing and distributing feed with built-in electronic devices for functioning and monitoring the technical condition (Gorobets *et al.*, 2018; Fuyang *et al.*, 2020). Equipping the mechanisms of loading, grinding-mixing, and unloading of feed mixture of feed dispensers with diagnostic devices using modern IT technologies will help fulfil their reliability as complex technical systems "Human-Machine-Environment" (Astanakulov *et al.*, 2020). Therewith, special importance is attached to the "human-operator" as a component of the sociotechnical system.

H.-W. Lo *et al.* (2019) noted that increasing the reliability of machines and reducing possible risks during the production process is crucial for ensuring the operability of research objects. The use of the method of failure analysis and at the same time maintaining the performance of the "human-machine" system is based on the experience of experts, involves the identification of their main types and the establishment of the most critical factors to prevent the risk of their occurrence. The results of the study confirmed the possibility of using logical-probabilistic modelling to analyse failures and ensure the reliability of equipment not only in animal husbandry, but also in mechanical engineering.

During the operation of the device, it was established that a certain number of failures were also caused by the lack of information on the criteria of the limit state of the drive parts in the guidance materials for the use of the device. The practice of using means for preparing and distributing feed has determined that the complex cause of failure of the feed mixture unloading mechanism is untimeliness or violation of the periodicity of control over the condition of parts and regulation of the main parameters of the technical condition. The study presents the results of theoretical and experimental studies of the reliability of means for the preparation and distribution of feed as complex technical systems depending on the influence of the components "human-operator", "machine", "environment" based on logical simulation modelling.

CONCLUSIONS

According to the study results, the distribution of failures of means for preparing and distributing feed as a complex technical system "Human-Machine-Environment" was highlighted, a logic-probabilistic model of failure formation was obtained. The logical-probabilistic model of formation of the failure of the feed mixture unloading mechanism factors in the influence of the components "machine", "person", "environment". Using a logical-probabilistic model and analytical dependencies, the probabilities of

failure of the feed mixture unloading mechanism under several conditions were investigated. The first condition is insufficient qualification of the operator, the second is failure of the drive parts; the third is untimeliness of adjustment of the mechanism. Research has established that the "human-operator" component, i.e., r_1, has a predominant influence on the probability of failure of the feed mixture unloading mechanism. The probability of failure of the mechanism is less important under the condition that the probability of eliminating the failure of the mechanism due to insufficient qualification of the operator and the failure of the drive parts r_5 is 0.2, and the mechanism is untimely adjusted with a probability of 0.99. An increase in the probability of failure of the operator's work under the condition of insufficient qualification r_1, from 0.5 to 0.9 leads to an increase in the probability of failure due to a change in the conveyor tension and the impossibility of adjusting the conveyor tension $r_{7\text{-}8}$. Therewith, the probability of $P_{7\text{-}8}$ failure within 0.5 to 0.99 will increase intensively and will reach a maximum value of 0.046.

In further studies, possible areas for increasing the reliability of the feed mixture unloading mechanism for preparing and distributing feed will be considered: research and formation of measures to reduce the probability of mechanism failures as a result of untimeliness of the error elimination by the operator; research of the logical-probabilistic model of the formation of failures depending on the influence of the external environment; formation of feedback with machine manufacturers regarding the formation and implementation of a reliability program at the design and manufacturing stages.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Логіко-імовірнісна модель оцінки надійності засобів для приготування і роздавання кормів

Анотація. У сучасному етапі розвитку тваринництва все більш поширеними стають засоби, які використовуються для приготування і подачі кормових сумішей. Ці засоби поєднують у собі операції завантаження, подрібнення, змішування, транспортування та дозованої роздачі кормів. Метою статті була оцінка і забезпечення надійності експлуатації засобів для приготування і роздавання кормів за рахунок логіко-імовірнісного моделювання виникнення відмов механізму вивантаження кормової суміші як підсистеми технічної системи «Людина-Машина-Середовище». В досліджені було використано логіко-імовірнісне моделювання засобів для приготування і роздавання кормів як складних технічних систем в залежності від впливу складових «людина-оператор», «машина», «середовище». Проаналізовано найкоротші шляхи виникнення відмов та мінімальні перерізи їх попередження для об'єктів дослідження. Доведено, що для запобігання відмови складової системи «людина-оператор» слід забезпечувати достатню кваліфікацію персоналу, передбачати можливе виникнення помилок та забезпечувати своєчасне їх усунення. Підтверджено, що для запобігання відмов механізму вивантаження кормової суміші необхідно своєчасно проводити контроль та регулювання стану деталей в процесі експлуатації та при відновленні працездатності. Встановлено, що ймовірність виникнення відмови механізму буде мати менше значення при умові, що ймовірності усунення відмов при недостатній кваліфікації оператора та при відмові деталей приводу будуть становити 0,2. Виявлено, що збільшення значення ймовірності відмови роботи оператора за умови недостатньої кваліфікації, з 0,5 до 0,9 призведе до збільшення ймовірності відмови в результаті зміни натягу транспортеру та неможливості регулювання натягу транспортеру, а при 0,9 ймовірність відмови механізму буде становити 0,046. Практичне значення результатів полягає в можливості дослідження ймовірності виникнення відмов механізму вивантаження кормової суміші виходячи з надійності складових засобу для приготування і роздавання кормів, включаючи деталі приводу, полотна транспортера

Ключові слова: надійність машин; складна технічна система; механізм вивантаження кормової суміші; людина-оператор; середовище